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Flow rate analysis of wastewater inside reactor tanks on tofu wastewater treatment plant

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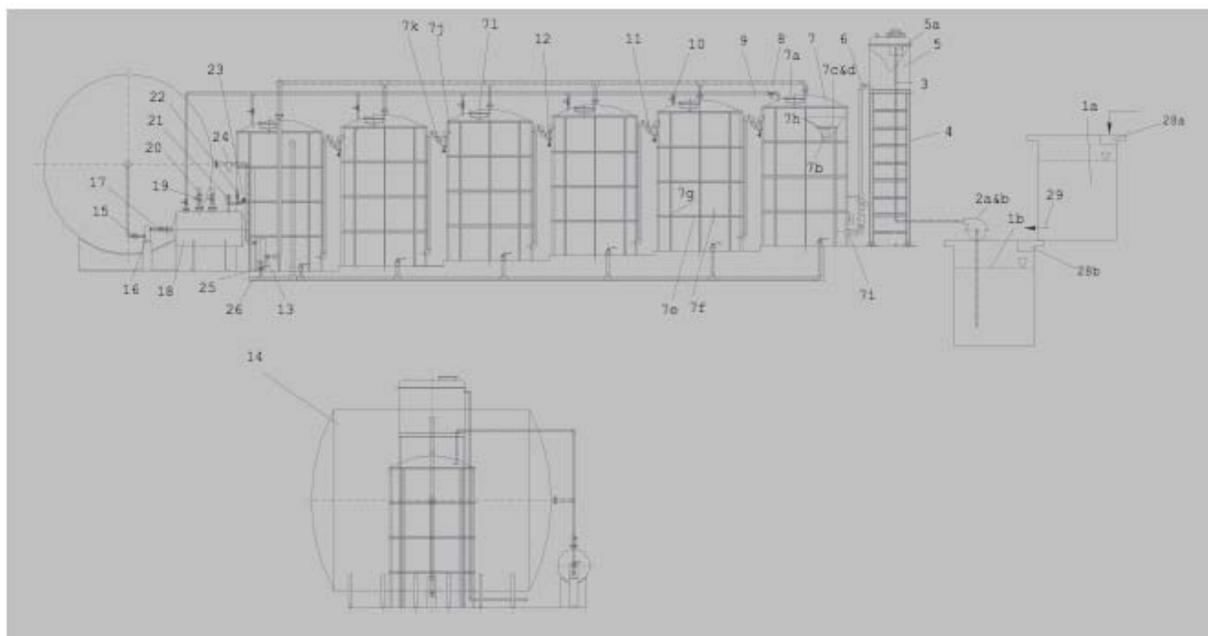
Abstract. The research aimed to analyse the flow rate of the wastewater inside reactor tanks which were placed a number of bamboo cutting. The resistance of wastewater flow inside reactor tanks might not be occurred and produce biogas fuel optimally. Wastewater from eleven tofu factories was treated by multi-stages anaerobic process to reduce its organic pollutant and produce biogas. Biogas plant has six reactor tanks of which its capacity for waste water and gas dome was 18 m³ and 4.5 m³, respectively. Wastewater was pumped from collecting ponds to reactors by either serial or parallel way. Maximum pump capacity, head, and electrical motor power was 5m³/h, 50m, and 0.75HP, consecutively. Maximum pressure of biogas inside the reactor tanks was 55 mbar higher than atmosphere pressure. A number of 1,400 pieces of cutting bamboo at 50-60 mm diameter and 100 mm length were used as bacteria growth media inside each reactor tank, covering around 14,287 m² bamboo area, and cross section area of inner reactor was 4,9 m². In each reactor, a 6 inches PVC pipe was installed vertically as channel. When channels inside reactor were opened, flow rate of wastewater was 6x10⁻¹ L.sec⁻¹. Contrary, when channels were closed on the upper part, wastewater flow inside the first reactor affected and increased gas dome. Initially, wastewater flowed into each reactor by a gravity mode with head difference between the second and third reactor was 15x10⁻²m. However, head loss at the second reactor was equal to the third reactor by 8,422 x 10⁻⁴m. As result, wastewater flow at the second and third reactors were stagnant. To overcome the problem pump in each reactor should be installed in serial mode. In order to reach the output from the first reactor and the others would be equal, and biogas space was not filled by wastewater, therefore biogas production will be optimum.

1. Introduction

A multi-stages biogas plant which was built in Giriharja, Kebonjati village, Sumedang district could treat 18-20 m³. day⁻¹ wastewater from eleven local tofu factories. This wastewater contains 7000-8000 gr COD.L⁻¹ that exceeds the effluent standard for soybean-based industry. By wastewater treatment, the tofu factories could comply an environmental regulation, and the water safely discharged into Cileuweung River. Tofu production resulted two types of wastewater namely the dilute and concentrated wastewater, both of wastewater was then collected into the ponds. Dilute wastewater was then fed to reactor to be processed anaerobically to produce biogas. The biogas plant has 6 reactor tanks, every three reactor tanks were set up serial mode with capacity of each reactor tank is 18 m³ of wastewater and 4.5 m³ of biogas. Biogas production was designed until 120 m³.day⁻¹ of gas as an LPG substitution for 91 households.



Wastewater collected in the pond was pumped into equalizing tank and drained by gravity to all reactors. Bamboo as bacteria growth media were placed horizontally on each reactor, between buffer zone, which may cause a resistance of wastewater flow rate. Due to bamboo placed between barriers, it caused a resistance to wastewater flow and raised the wastewater level inside reactor tanks. Therefore, space of biogas was occupied by wastewater. Consequently, biogas was not produced. Therefore, flow rate input was not equal to its output, resulted wastewater level inside the first, second, fourth, and fifth tanks were higher than the set up levels. This configuration was set as shown in Figure 1.



Notation: 1a. Upper storage, 1b. Lower storage, 2a&b. Pump machines, 3. Wastewater pipe, 4.Support, 5. Equalizing tank, 5a. Filter, 6. Inlet pipe, 7. Reactor tank, 7a. Manhole, 7b. Bamboo cutting, 7c&d. Reinforce, 7e. Reinforce ring, 7f. Bolt nut, 7g. Vertical reinforce, 7h.Nylon net, 7i.Anchore, 8. Gas pipe, 9. Back wash pipe, 10. Back wash valve, 11.Outlet pipe, 12. Valve, 13. Gas flow meter, 13. Gas scrubber, 14. Gas holder, 15. Gas valve, 16. Gas compressor, 17.Check valve, 18. Distribution tank, 19. Back wash valve, 20. Gas valve, 21.Pressure gauge, 22. Relief valve, 23. Gas pipe, 24. Sight glass, 25. Concrete base, 26. Drain pipe.

Figure 1. Arrangement of reactor tanks.

At the beginning, wastewater flowed from the first reactor to another by gravity mode with a head difference of each reactor was 0.15 m. An analysis based on observations, theory of fluid mechanic and discussion, it could be known that reactor head loss was lower than head losses at each reactor, therefore flow stagnation was occurred at the second and third reactor for the first unit, and at the fifth and the sixth for the second unit. When a remained of biogas space was occupied by wastewater, the condition could decrease biogas production.

This research aimed to solve problem caused by a resistance of wastewater flow rate occurred inside existing reactor tanks filled with bamboo, therefore the ideal flow rate of wastewater inside reactor tank could be created to produce biogas optimally.

2. Experimental

2.1. Materials

Reactor tanks were built by 10 mm-thickness composite materials with 2500 mm in diameter, 4000 mm height, and 650 mm dome height. The reactor tanks have a space of 80% wastewater and 20% of biogas. Tofu wastewater was pumped from the collection pond into an equalizing tank and distributed to all reactors. Capacity of pump is $5 \text{ m}^3 \cdot \text{hr}^{-1}$ and its head is 50 m operated by an electrical power of

motor at 0.75 HP [1]. Equipment that applied at the experiment were water flow meter, stop watch, ball valve and water pump.

2.2. Experimental setup

Each reactor tank was equipped with bottom and top buffers, where perforated-corrugated composites at bottom and nylon nets at top barriers with 2000 mm distance were set up and in between were filled by 1400 pieces bamboo cutting as bacteria growth media to produce methane gas. Each bamboo has 50-80 mm in diameter and 100 mm length. The 2500 mm diameter and 3 mm thickness bottom barrier [2] has 200 holes and each hole has a 50 mm in diameter. The nylon net as a top barrier which was submerged at 1200 mm below water level has a (30x30) mm² hole.

Residence time of wastewater existing inside each reactor is about eight hr before the wastewater moved to the next reactors. Initial pH of wastewater was 4.5-5.0 and wastewater pH at the effluent must be around neutral.

Inlet and outlet of reactors were equipped a water flow meter, therefore fed and drained wastewater quantity could be recorded.

2.3. Calculations

To analyse the flow rate of wastewater inside the reactor tanks, the steady flow equation for unit mass flow rate under uniform was applied, continuous flow condition based on Figure 2.

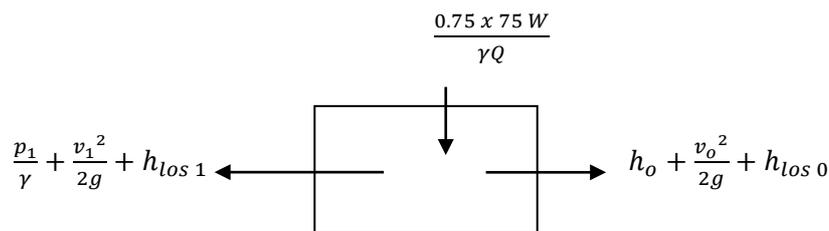


Figure 2. Energy balance.

Energy needed to raise wastewater from collection ponds to pump machine is $\dot{m} \left(\frac{v_o^2}{2g} + h_o + h_{los0} \right)$, while energy needed to press wastewater flowed to reactor tank is $\dot{m} \left(\frac{v_1^2}{2g} + \frac{p_1}{\gamma} + h_{los1} \right)$ and power of pump obtained is $\dot{m} \left(\frac{0.75 \times 75 W}{\gamma \dot{Q}} \right)$. Where inlet velocity of wastewater to pump is $v_o (m/sec)$, outlet velocity of wastewater from pump is $v_1 (m/sec)$, head wastewater level in collection pond is $h_o (m)$, static pressure of wastewater went out from pump is $p_1 (kg/m^2)$, head losses of inlet is $h_{los0} (m)$, head losses of outlet is $h_{los1} (m)$, power of pump is $W (kgm/sec)$, flow rate of wastewater is $\dot{Q} (m^3/sec)$, density of wastewater is $\gamma (kg/m^3)$ and gravity is $g (m/sec^2)$. Thereby an equation of energy balance could be obtained as follows:

$\frac{56.25W}{\gamma \dot{Q}} = \frac{p_1}{\gamma} + \frac{v_o^2 + v_1^2}{2g} + h_o + h_{los0} + h_{los1}$, diameter of inlet pipe was equal to outlet pipe and $v_o = v_1$, therefore outlet velocity of the pump could be obtained by an equation (1).

$$v_1 = \sqrt{2g \left\{ \left(\frac{56.25W}{\gamma \dot{Q}} \right) - \left[\frac{p_1 + \gamma(h_o + h_{los0} + h_{los1})}{\gamma} \right] \right\}} \quad (1)$$

Actual head of the pump could be obtained by an equation of $\frac{v_1^2}{2g}$ equal h_p .

Head losses occurred at wastewater flow to reactor depends on some factors, such as: friction of flow on wall face, bend flow, expansion and contraction flow. Particulate number contained by wastewater had a significant effect on a friction at pipe wall and vessel. The condition could be assumed as a face roughness of drain wall, and friction value affected by wall roughness of $k (mm)$,

length of pipeline is l (m), diameter of pipeline is D (m) and Reynolds number dimensionless. Friction value of wastewater flow could be obtained by an equation as follows:

$$f = 0.001375 \left[1 + \left(200 \frac{k}{D} + \frac{10^6}{R} \right)^{\frac{1}{3}} \right] \quad (2)$$

Head losses caused by some factors for examples; contraction factor, expansion factor, friction factor, bend factor, and discharge factor. Contraction and expansion factor obtained from graphic of area ratio versus contraction and expansion factor. Head losses factor of bend, tee joint, foot valve, ball valve and check valve, therefore could be obtained by [3]. Head losses at pump inlet caused by energy needed to raise wastewater from collection ponds to pump machine, friction of pipe wall, bend and contraction caused a diameter difference between inlet and outlet of pump. Therefore head losses of pump inlet could be obtained by an equation as follows [4]:

$$h_{los} = \left(f \frac{l}{d} + k_{fv} + k_v + k_{cv} + k_T + k_k + k_c + k_e \right) \frac{v_1^2}{2g} \quad (3)$$

where head losses factor of foot valve is k_{fv} , had losses factor of ball valve is k_v , head losses factor of check valve is k_{cv} , head losses factor of tee joint is k_T , head losses factor of knee is k_k , head losses factor of contraction is k_c , and head losses factor of expansion is k_e .

Inlet to the first reactor tank formed velocity of wastewater pumped which was might higher than head losses of bamboo cutting, head of wastewater inside reactor tank and pressure of biogas. Head losses at the first reactor tank, which was lower than head of pump and could be formulated by an equation as follows:

$$h_r + p_g + h_{loss} < h_p \quad (4)$$

Wastewater inside the first reactor had to flow into the second reactor and wastewater inside the second reactor had to flow into the third reactor then went out from the third reactor tank to the collection ponds. Head differences between the first reactors was equalled to the second and the third that is h_r (m). Based on Figure 2, outlet of the first reactor be analysed using equation as follows:

$$\frac{p_1}{\gamma} = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + h_{los2} + h_2 \quad (5)$$

Wastewater flowed from the first reactor to the second and the third one, when each head difference of reactor tanks must more than head losses of bamboo cutting, expansion, contraction and friction. Therefore flow rate of reactor output could be obtained by an equation as follows [5]:

$$\dot{Q}_r = c_d A v \quad (6)$$

Flow rate of reactor tank output is \dot{Q}_r (m^3/sec), discharge factor is c_d , discharge area of reactor tank is A (m^2) and wastewater velocity is v (m/sec).

3. Result and discussion

3.1 Flow rate observation

The results show that wastewater density was $1,050 \text{ kg.m}^{-3}$, inlet pipe of pump was equipped a foot valve losses factor was 1.55, at pipeline from collection ponds equipped a 10 standard 90° elbows, and losses factor of each elbow was 0.9, therefore losses factor obtained was 9, the pipeline equipped by two ball valves and losses factor of each ball valve was 10, therefore losses factor of ball valves obtained was 20, pipeline length from pump machine to the reactor was 26m and roughness of pipeline was $15 \times 10^{-5} \text{ mm}$, wastewater velocity was 0.708 m.sec^{-1} , pipeline diameter was $5 \times 10^{-2} \text{ m}$, kinematic viscosity was $0.804 \times 10^{-6} \text{ cs}$, Reynolds number was 17.7×10^3 , therefore $Re > 2100$. It means that turbulent flow will occur.

Wastewater contained particulate of soybeans, therefore it was assumed that those roughness was $45 \times 10^{-3} \text{ mm}$. Thereby friction factor could be obtained by an equation (2) that was 10.67×10^{-5} . Pump capacity of 1.39 L.sec^{-1} and wastewater contained particulate of soy beans roughness of particulate was $45 \times 10^{-3} \text{ mm}$. Based on an equation (3), head losses occurred at inlet pipeline to reactor could obtained be 1.6528 m. Wastewater velocity inside reactor obtained was $2.8367 \times 10^{-4} \text{ m.sec}^{-1}$, inlet diameter of pipe was 100mm, so velocity of wastewater flowed inside pipe $17.7 \times 10^{-2} \text{ m.sec}^{-1}$. Cross section of bamboo was $94.2 \times 10^{-4} \text{ m}^2$ and the clearance between bamboo were tightly, therefore velocity of

wastewater flowed passed among bamboo could be $1.15 \times 10^{-3} \text{ m}\cdot\text{sec}^{-1}$, velocity of wastewater passed screen obtained was $55.33 \times 10^{-2} \text{ m}\cdot\text{sec}^{-1}$, velocity of wastewater flowed inside reactor obtained was $4.43 \times 10^{-2} \text{ m}\cdot\text{sec}^{-1}$ and velocity of wastewater flowed passed buffer hole obtained was $35 \times 10^{-4} \text{ m}\cdot\text{sec}^{-1}$. Thereby Reynolds number obtained was $56.135 \times 10^4 > 2100$, so wastewater flowed to pass bamboo would be a turbulent mode, while friction factor at bamboo obtained was 46×10^{-4} . Therefore head losses occurred at the reactor obtained was $84.22 \times 10^{-2} \text{ m}$.

Biogas pressure inside reactor tank was set up at 55 mbar or 550 mmH₂O, therefore total head losses obtained was 11.295 m, it was lower than head pump. Therefore, wastewater could flow inside reactors. Discharge factor obtained was 98×10^{-2} and contraction factor obtained was 0.8, wastewater velocity went out from buffer obtained was $2.8 \times 10^{-4} \text{ m}\cdot\text{sec}^{-1}$ and wastewater velocity inside outlet pipe obtained was $0.175 \text{ m}\cdot\text{sec}^{-1}$. Based on equation (6), wastewater output of the first reactor obtained was $1.08 \times 10^{-3} \text{ L}\cdot\text{sec}^{-1}$. In the experiment a number of 1400 pieces of bamboo cutting were placed inside all reactor tanks, wastewater in the ponds pumped into equalizing tank and flowed by gravity way to reactor tanks. Each reactor equipped by a float stick to indicate wastewater increase inside reactor tank. When the channel cup was opened wastewater from equalizing tank to the first and second reactor tank flowed in normal way. On the contrary, when the channel cup was closed wastewater flow was stagnant, therefore a float stick raise at 42.5 cm for only in 27 min, therefore wastewater occupied gas space in the first reactor other reactors as well. Experiment data were presented in Table 1.

Table 1. Flow rate observation.

Trial order	Time Observation (min)	Δh_{Stick} (cm)
1	5	30.0
2	5	38.0
3	25	41.5
4	12	42.0

These data show that wastewater flow from the first to other reactors was resistance, therefore wastewater occupied biogas space.

3.2 Energy consumption

To prevent the accident and to obtain an optimum of biogas production, a channel was installed to reduce resistant of wastewater flow rate at $0.6 \text{ L}\cdot\text{sec}^{-1}$, therefore wastewater level inside the reactor was concur with the level of output drain. Therefore, based on analysis amount of bamboo cutting placed inside each reactor should not more than 1400 pieces and channelled.

Input and output of drained pipe was of 50 mm in diameter, 100 mm length, number of bamboo was of 1400 pieces, 50-60 mm bamboo diameter, 100 mm bamboo length, 1.8 m^3 volumes of equalizing tank, difference of height between equalizing and reactor tank is 600mm, input drain was installed at 400 mm and output drain at 3,600 mm from bottom of reactors. Cross section of equalizing tank is 1.2 m^2 and cross section of reactor tank is 4.9 m^2 . The velocity of wastewater flow inside pipe obtained was $1.085 \text{ m}\cdot\text{sec}^{-1}$, ambient temperature of 30°C, kinematic viscosity of $804 \times 10^{-3} \text{ cs}$ or $8.04 \times 10^{-7} \text{ m}^2\cdot\text{sec}^{-1}$, Reynolds number was 6,747. It was higher than 2,300, therefore the flow of wastewater inside pipe was a turbulent flow. Based on the equation (1) the addition of bamboo cutting placed in the reactor increased the flow rate resistant. The time consumption by wastewater flowed from the first to the last reactor was 351 to 1,961sec. Therefore, flow rate of wastewater went out from drain-out pipe of the last reactor could be 150 to 1,925 $\text{L}\cdot\text{hr}^{-1}$. The value of roughness (k) of materials commonly used to manufacture pipe is 0 to 10^{-4} mm , based on the equations (2) and (3) friction factor obtained was 865×10^{-5} .

Number of bamboo inside reactor was 1400 pieces and flow rate of wastewater went out from reactor was $69 \times 10^{-3} \text{ L}\cdot\text{sec}^{-1}$. It was small wastewater output in comparison with the demand for fermentation process. The heads between reactor tanks were 0.15 m, gas space among reactors were

connected each other, therefore gas pressure at each reactor tank was balanced. Head losses of reactors were higher than head of reactor tanks, therefore wastewater inside the reactor difficult to flow to the other reactors. To increase wastewater flowrate, therefore inside reactor tanks were completed by perforated channels built from PVC pipe schedule AW with 150 mm inside diameter installed between the both buffer plates.

Wastewater flow rate obtained was 6×10^{-1} L.sec⁻¹ and most of wastewater flowed through the perforated channel tube. Wastewater flow rate demand for the aerobic process at the reactor was 625×10^{-3} L.sec⁻¹. Therefore, flow rate of wastewater went into reactor still less than 25×10^{-2} L.sec⁻¹. The channel tube was 100 holes-perforated and having 13mm in diameter. So the objective of installing the channel tube is to reduce resistant of wastewater flow and to change saturated wastewater by fresh one by setting up the time. When residence time is 10hr, wastewater flow rate achieved was 21,600 L for 10 hr, it was higher than flow rate needed at about 17,280 L.

When the channel tube was closed, it was no wastewater went out from reactor, however, after 30 min wastewater went out from reactor at flowrate of 69×10^{-3} L.sec⁻¹, therefore it was impossible that output of reactor at opened channel was lower than the closed one. This is because barrier plate was opened, the case was caused by wastewater pressure at bamboo cutting and barrier plate. The condition was not ideal, because food supply for bacteria was not sufficient.

When top barrier plate was changed with nylon net and the channel was closed, wastewater level inside the first reactor tank raised 42 cm on 22 min, therefore wastewater filled the gas space. The condition was also occurred at the second reactor. Number of bamboo cutting inside reactor was 1,400 pieces and head losses achieved was $8,422 \times 10^{-4}$ m. It was higher than head of wastewater inside reactor 15×10^{-2} m, therefore wastewater difficult to flow out from reactor, it could be shown in Table 1. The condition inside reactor, the wastewater filled the biogas space, therefore biogas production from the reactor could not be achieved optimally.

To overcome the case, therefore each reactor equipped with two pump machine different types, i.e.: (1) A centrifugal pump to supply wastewater to the first and the fourth reactor tanks which has capacity of 1.11 L.sec⁻¹ and head of 20 m, (2) A magnetic pump at capacity of 1 L.sec⁻¹, 6 m head and 100 watt power to supply wastewater to the other tanks. The head of both pumps were higher than head losses, therefore wastewater could flow well as capacity needed from the first to other reactors. Thereby, wastewater inside reactor did not occupy the biogas space, therefore biogas production could be optimum.

Existing bamboo cutting inside reactors caused resistance and affected flow rate of wastewater inside reactors, the more bamboo cutting inside reactors the higher resistance occurred and the less wastewater discharged from reactors. Number of bamboo cutting inside every reactor were the same and hope that wastewater flow inside reactor tanks could achieve a balance between input and output. New arrangement of the reactor tanks is shown in Figure 3.

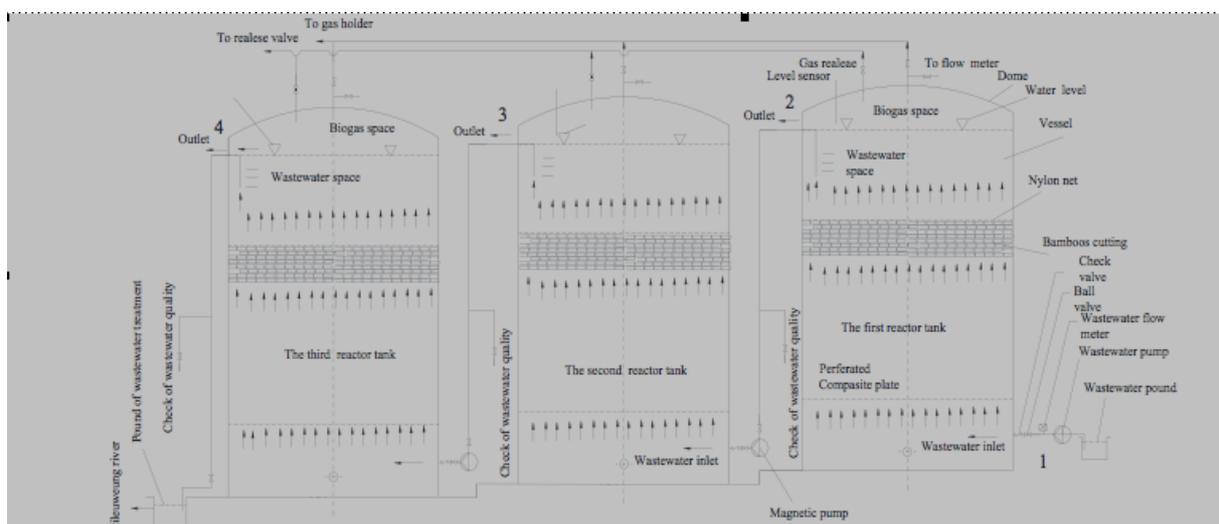


Figure 3. New arrangement of reactor tanks.

Notation: 1. Wastewater inlet to the first reactor tank, 2. Wastewater outlet of the first reactor tank and inlet for the second reactor tank, 3. Wastewater outlet from second reactor tank and inlet for the third reactor tank, 4. Wastewater outlet of third reactor tank.

4. Conclusion

When the number of bamboo cutting was 1400 pieces and placed tightly at horizontal position, head losses occurred at each reactor tank was 8.42×10^{-1} m and it was higher than head reactor tank of 1.5×10^{-1} m. The first reactor completed by a pump at capacity of $1.39 \text{ L}\cdot\text{sec}^{-1}$ and head of 30 m, therefore wastewater at the first reactor could flow well. On the contrary, the second and the third reactors without pump installation caused the wastewater could not flow optimally, therefore as a consequence the wastewater filled the biogas space. With pumps installed in every reactor, there is no resistance of wastewater flow inside reactors. The quantity of bamboo cutting, however, could be added on every reactor to increase the bacteria growth media, so the biogas produced optimally.

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